Prediction of energetic particle confinement in ITER operation scenarios

Z. Lin[1], E. Bass[2], G. Brochard[1,3], Y. Ghai[4], N. Gorelenkov[5], M. Idouakass[6], C. Liu[5], P. Liu[1], M. Podesta[5], D. Spong[4], X. Wei[1], W. Heidbrink[1], R. Waltz[7], J. Bao[8], V. Duarte[5], M. Gorelenkova[5], T. Hayward-Schneider[9], S. H. Kim[3], J. Nicolau[1], S. D. Pinches[3], A. Polevoi[3], M. Schneider[3]
Email: zhihongl@uci.edu
[1] University of California, Irvine, CA 92697, USA
[2] University of California, San Diego, CA 92093, USA
[3] ITER organisation, Route de Vinon-sur-Verdon, CS 90 046 13067 St., Paul Lez Durance, France
[4] Oak Ridge National Laboratory, Oak Ridge, Tennessee 36831, USA
[5] PPPL, Princeton University, Princeton, NJ 08543, USA
[6] National Institute for Fusion Science, 322-6 Oroshi-cho, Toki, Gifu 509-5292, Japan
[7] General Atomics, PO Box 85608, San Diego, CA 92186-5608, USA
[8] Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China
[9] Max-Planck-Institut für Plasmaphysik, Boltzmannstr. 2, 85748 Garching, Germany

Large scale simulations of energetic particle (EP) confinement in the ITER operation scenarios, validated using matching DIII-D experiments, find that macroscopic fishbone can be unstable, but saturate at a low amplitude with insignificant distortion of flux surface and EP re-distribution. Various meso-scale Alfven eigenmodes (AE) saturate at high amplitudes and drive a large EP transport, which results in a modest flattening of the EP profiles during the short simulation time. Strong microturbulence drives directly little EP transport but large thermal transport, which could affect EP transport driven by the AE and fishbone. These studies point to a modestly optimistic assessment of the EP confinement in the ITER, but also a significant relaxation of the alpha particle profile in the steady state scenario. Finally, integrated simulation of cross-scale coupling is needed to reliably predict EP confinement in the ITER, as demonstrated in the simulations of the DIII-D experiments.

Background— EP transport in burning plasmas can be induced by macroscopic MHD modes, meso-scale AE, and microturbulence, which could interact nonlinearly. In this project, EP confinement properties of the ITER operation scenarios have been comprehensively assessed using global gyrokinetic codes (GTC, GYRO, ORB5), kinetic-MHD codes (FAR3D, GAM-solver, M3D-C1, MEGA, NOVA-C, XTOR-K), and reduced EP transport models (CGM, Kick, RBQ). These codes have been first verified and validated for simulations of EP transport in the DIII-D experiments. The comparisons between DIII-D experiments and ITER scenarios provide physics insights on the extrapolation from existing fusion experiments to the future burning plasma experiments. This collaborative research has been selected for US DOE FY2022 Theory Performance Target and adapted as the ITPA energetic particle joint activity B.11.12 project. This paper summarizes key results from this large international collaboration. More detailed results will be reported by other papers [1-4] submitted to this conference.

Prediction of EP confinement in ITER— After extensive discussions within the EP community, two ITER scenarios: a baseline pre-fusion (BL, shot #101006) and a steady state fusion (SS, shot #131041), have been selected and IMAS equilibrium data have been provided by ITER-IO researchers. To validate the ITER simulations, two existing DIII-D shots (BL shot #178631, SS shot #132708) with similar safety factors and EP instabilities as the two ITER scenarios have been selected by the DIII-D experimental collaborators. Comprehensive simulations find that the DIII-D and ITER have very similar linear instabilities, thus DIII-D experiments provide an excellent validation for the ITER simulations.

Global gyrokinetic and kinetic-MHD simulations find that fishbone is excited by the NBI EP density gradients and saturates at a low amplitude with insignificant distortion of flux surface and EP re-distribution in the ITER and DIII-D BL. The fishbone is stable in the ITER and DIII-D SS.

Gyrokinetic, kinetic-MHD, and reduced transport model simulations find that various AEs are excited by both NBI and alpha EP density gradients and saturate at high amplitudes in the ITER and DIII-D SS. A strong EP transport is driven, which results in a modest flattening of both the NBI and alpha EP radial profiles in the ITER SS within the short simulation time. AEs are marginally stable or weakly unstable in the ITER and DIII-D BL.

Gyrokinetic simulations find that strong microturbulence in both SS and BL scenarios of the ITER and DIII-D drives little EP but large thermal transport. Microturbulence could affect AE & fishbone that drive a larger EP transport [5].

In summary, these simulations indicate that NBI EP is well confined in the ITER pre-fusion BL scenario and that both NBI and alpha in the ITER fusion SS scenario could be subjected to significant transport by AEs. However, quantitative prediction of the EP transport needs further integrated simulations coupling MHD, AEs, and microturbulence to incorporate cross-scale interactions.

New EP physics discovered through simulations— An exciting finding from global gyrokinetic simulation is that the fishbones in both the DIII-D and ITER BL saturate by zonal flows. Simulations including zonal flows agree quantitatively, for the first time, with the DIII-D experiment regarding mode amplitude and EP transport manifested as neutron emissivity drop. Furthermore, zonal flows generated by the fishbone can suppress thermal plasma transport driven by the microturbulence, consistent with the formation of internal transport barrier after the fishbone bursts in the DIII-D experiment.

Another important physics finding from gyrokinetic, kinetic-MHD, and reduced transport model simulations is that nonlinear interactions of many unstable AEs with a large number of mode rational surfaces lead to a large quasi-steady state EP transport in the ITER SS. Figure 1 shows that GTC gyrokinetic and MEGA kinetic-MHD simulations both find very large NBI and α-particle diffusivities during a short time scale (~0.1ms) despite very different simulation models. In contrast, EP transport quickly diminishes after AE saturation in the DIII-D experiment where only a few AEs are unstable as shown in gyrokinetic simulations artificially suppressing the microturbulence[5].

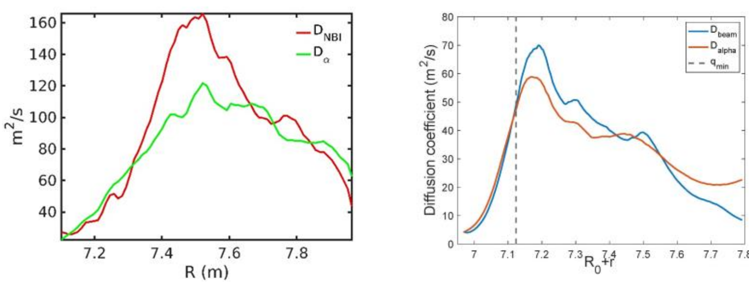

Fig. 1: *Radius profiles of NBI beam and α-particle diffusivities during a short time scale (~0.1ms) from GTC (left panel) and MEGA (right panel) simulations of AEs in ITER SS.*

References:

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